HYDRAULIC TUNNELING IN ST. PETER SANDSTONE AT MINNEAPOLIS, MINN.

By **Walter E. Lewis**

* * * * * * * * * **Information Circular 7571**

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CONTENTS

	Page
Introduction and summary	1
Acknowledgments	1
Character of St. Peter sandstone	2
Hydraulic mining method	3
Removal of sand	5
Tunnel support	7
Steel arch support	7
Steel liner plates	8
Skin-tight	8
Ventilation	9
Drainage	10
Hydraulic tunneling cost	10

ILLUSTRATIONS

Fig.		Follows page
1.	Cutting a caved block of St. Peter sandstone and washing the resulting sand away from the face (Main storm sewer starting at 10th Avenue SE bridge, Minneapolis, Minn.)	2
2.	Face of tunnel with initial jet cuts and caved block of sandstone. (Main storm sewer starting at 10th Avenue SE bridge, Minneapolis, Minn.)	2
3.	Pump arrangement employed when tunneling has progressed past 4,000 feet	4
4.	The mobile "mucker" and "cutter" in operation. (Main storm sewer starting at 10th Avenue SE bridge, Minneapolis, Minn.)	4
5.	Mobile "mucker" and "cutter" in the heading of the tunnel. (Main storm sewer starting at 10th Avenue SE bridge, Minneapolis, Minn.)	4
6.	Types of tunnel support for main storm sewer, Minneapolis, Minn	6
7.	Changing over from steel liner plates to skin-tight method of tunnel supports. (Main storm sewer starting at 10th Avenue SE bridge, Minneapolis, Minn.)	8

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Information Circular 7571

INTRODUCTION AND SUMMARY

A method of cutting St. Peter sandstone by streams of water under pressure from nozzles and pumping the resulting sand to the surface has reduced the cost of storm-sewer construction in the Minneapolis-St. Paul area. The hydraulic tunneling method has been in use since 1934, and it is adaptable only to the lower part of the St. Peter sandstone, which lies within or just above the ground-water level. The upper part of the formation, immediately below the Platteville limestone, is cemented and cannot be mined by hydraulic methods.

The tunnel operation observed in this instance is a main storm sewer starting at the Mississippi River below the 10th Avenue SE bridge and will be driven 6,000 feet at a grade of 1 foot per thousand under the city of Minneapolis to Kennedy and Arthur Streets NE. A lateral storm sewer, which branches from the main sewer at 8th Street SE, will extend from 10th Avenue SE to 15th Avenue SE. The tunnels are being driven with the floor approximately at ground-water level. All waters entering the main storm sewer will drain into the Mississippi River.

The main storm sewer cross section is excavated to a roughly hexagonal shape 10 feet high by 10 feet wide at the center. The upper half of the tunnel section is solidly lined with either timber or steel. After all excavation is completed, the tunnel will be finished with a concrete circular lining 8 feet in inside diameter. The lateral storm sewer is excavated to a 5-1/2-foot by 7-1/2-foot section and will eventually be finished with concrete to a modified horseshoe-shaped section 6 feet by 4 feet. Where the back or walls are considered unsafe during excavation, the upper half of the tunnel is lined solidly with timber.

The equipment used by the Sewer Division, City of Minneapolis, has been selected to meet a number of applications in storm-sewer work with diversified usage in mind. The sand pumps used on this job are rubber-lined, designed to work against a head of 100 feet. Either 4-inch or 6-inch diameter suction and discharge openings may be used. Other equipment, such as pipe, mine rail, flexible hoses, compressors, and general surface shop equipment, is drawn from a central warehouse. It may be either new or used, depending on what is available at the warehouse. Much of the pipe and mine rail has been used for many years on several different tunnel jobs.

ACKNOWLEDGMENTS

The cooperation of the following officials of the Engineering Department, Sewer Division, City of Minneapolis, is gratefully acknowledged:

Robert Huston, sewer engineer
J. F. Durrigan, resident engineer
Alfred Enger, superintendent, construction
and maintenance
Charles Nee, assistant superintendent
Victor Hanson, cost accountant

Mr. Nee permitted free use of his records for the preparation of cost data in this report.

CHARACTER OF ST. PETER SANDSTONE

St. Peter sandstone is found in seven states of the central Mississippi Valley; namely, Minnesota, Wisconsin, Iowa, Illinois, Missouri, Arkansas, and Oklahoma; also, it is thought that it may be present in Indiana, Ohio, Kentucky, Michigan, Kansas and Nebraska.2/ The sandstone is a relatively pure siliceous sand composed of rounded transparent grains of quartz. The formation furnishes an excellent quality of glass sand and is mined extensively for that purpose. The formation is free of argillaceous or calcareous layers and is found in a wide range of colors, including white, green, brown, red, buff, yellow and salmon.

The St. Peter sandstone found in the 10th Avenue SE main storm sewer at Minneapolis is white with a faint brownish cast and its texture is variable. The upper part of the formation has been cemented by the iron and calcium salts carried from the overlying limestone and deposited in the intersitial spaces of the sandstone. The middle and lower parts of the formation are soft and friable in some portions, whereas, in others the sand grains are loosely cemented together, and a more or less indurated rock is formed. Cemented lumps are found occasionally within the soft and friable portion.

A representative sample of the hydraulically mined washed material was screen-tested at the Bureau of Mines laboratory at Minneapolis. Results are shown in table 1.

TABLE 1 - Screen test of washed St. Peter sandstone from the storm sewer starting at 10th Avenue SE bridge, Minneapolis, Minn.

Size, mesh	Openings, millimeters	Weighted, percent	Weight, percent accumulated
+28	0.589	All pass	-
-28 +35	.417	4.8	4.8
-35 +48	.295	30.7	35.5
-48 +65	.208	22.8	58.3
-65 +100	.147	17.1	75.4
-100 +150	.104	14.3	89.7
-150 +200	.074	9.2	98.9
-200		1.1	100.0

2/ Dake, C. L., Problem of the St. Peter Sandstone: School of Mines and Metallurgy, Rolla, Mo; Technical Series Bull. No. 1, Plate I following P.8, Plate III following P. 14, August 1921.

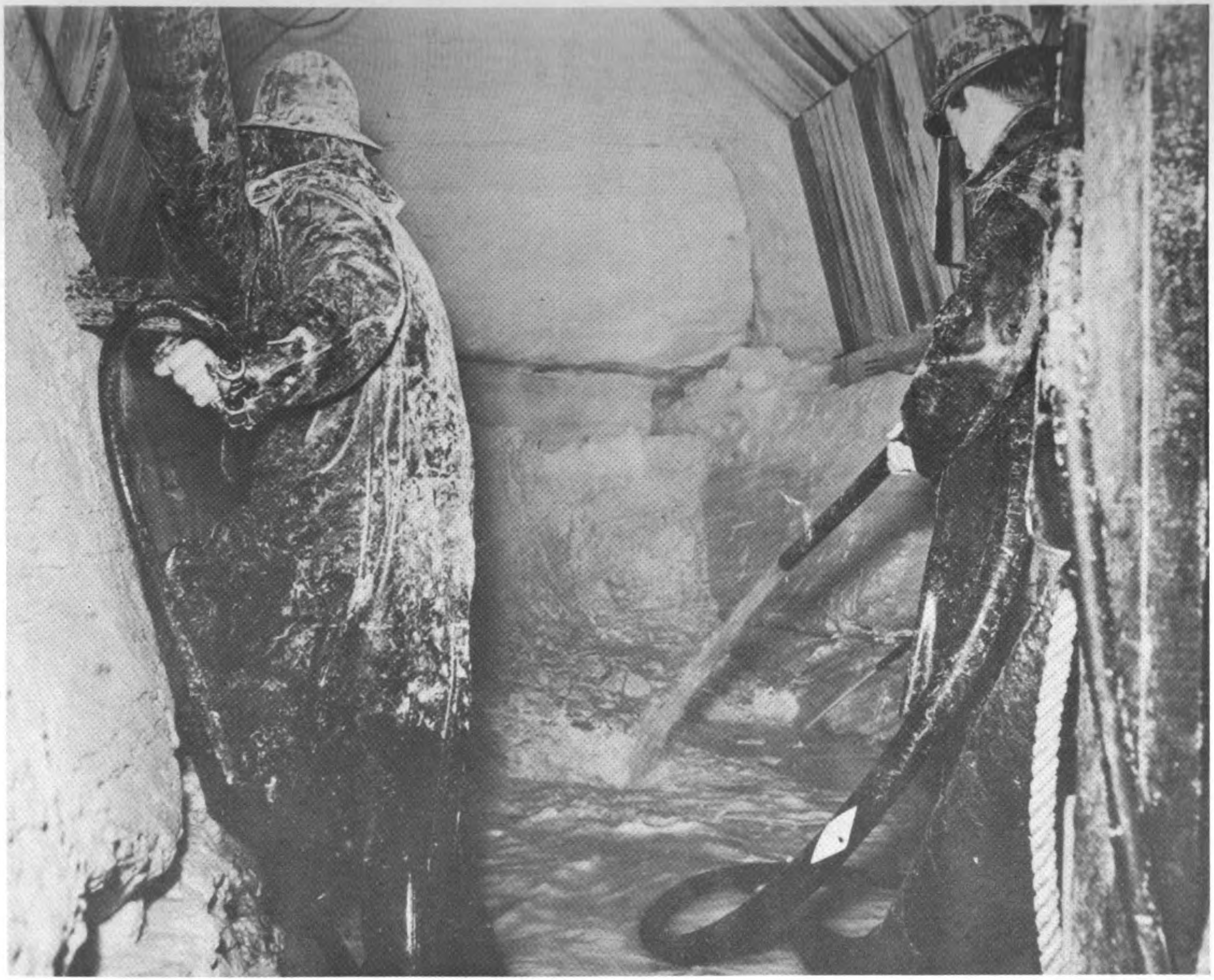


Figure 1. - Cutting a caved block of St. Peter sandstone and washing the resulting sand away from the face. (Main storm sewer starting at 10th Avenue SE bridge, Minneapolis, Minn.) (Courtesy, C. J. Kenison, Industrial Photography, Minneapolis, Minn.)

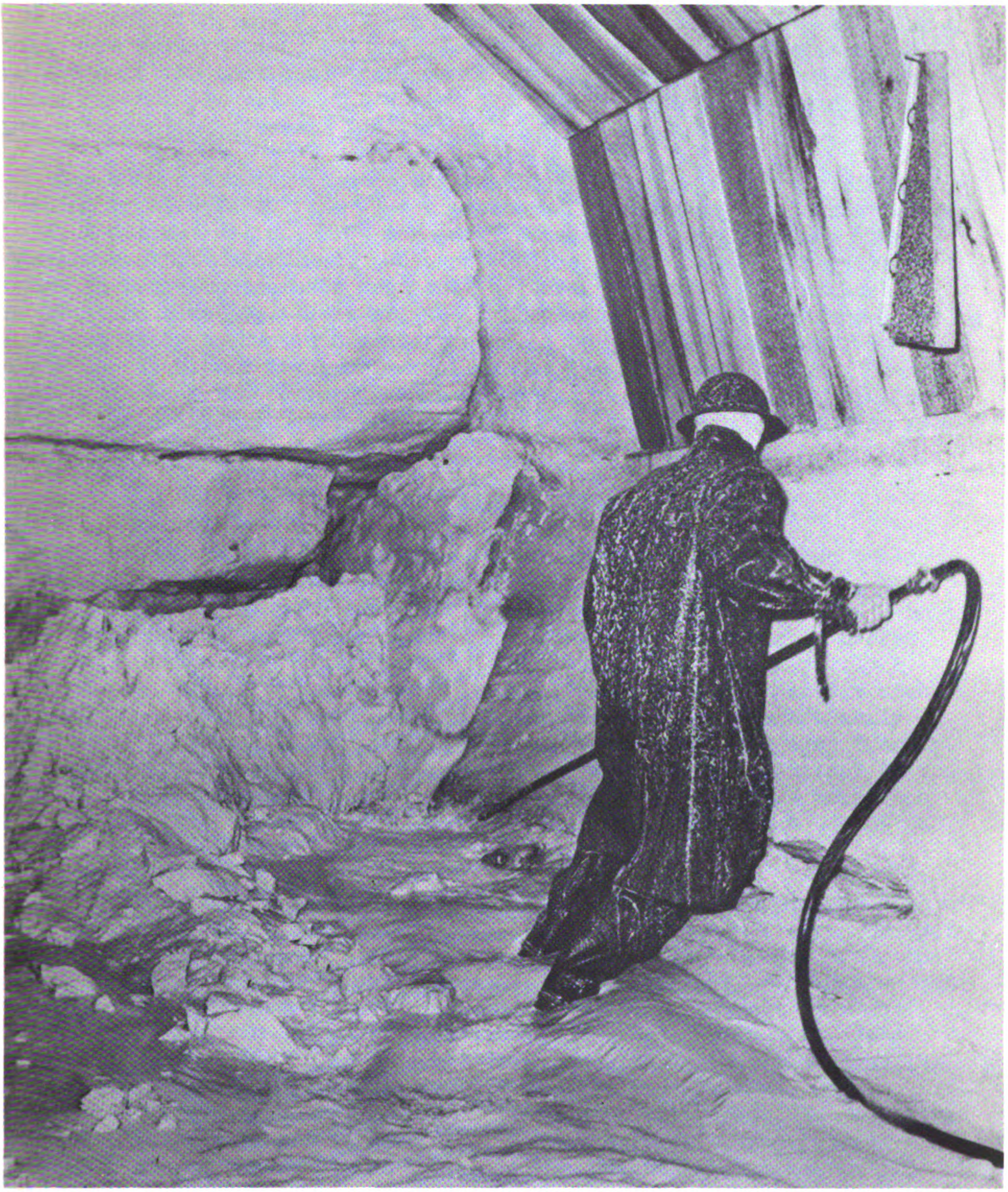


Figure 2. - Face of tunnel with initial jet cuts and caved block of sandstone. (Main storm sewer starting at 10th Avenue SE bridge, Minneapolis, Minn.) (Courtesy, C. J. Kenison, Industrial Photography, Minneapolis, Minn.)

Composition of the sample sized in table 1 was 99.64 percent silica, 0.02 percent iron, and 0.10 percent lime. The silica grains in all screen sizes were well-rounded, and the coarser sizes approach perfect spheres. The shape of the particles accounts for the free-flowing property of the washed grains. In place, the grains are held together to a variable degree by cementing minerals of iron, calcium, and magnesium.

The more strongly cemented portions of sandstone that are resistant to breaking by streams of water under pressure from nozzles have a composition of 97.94 percent silica, 0.04 percent iron and 0.14 percent lime. The magnesia was not determined. When encountered, this material requires a change in tunneling methods from cutting under pressure from nozzles to drilling and blasting. However, the broken material resulting from blasting is subsequently broken into small particles by jets, washed away from the face with water, and transported out of the tunnel by sand pumps. Usually, blasting loosens the cemented zones of sandstone sufficiently so that no difficulty is experienced in reducing the rock to sand and washing it away from the face.

HYDRAULIC MINING METHOD

The tunnel is normally advanced by cutting the rock with two streams of water under pressure from nozzles. Four men are employed at the face - two men direct the jets, a third man directs a flow of water from a 2-inch wash hose, and the fourth man tends the pumps. The sandstone is broken into small particles, partly by direct impact of the jets and partly by undercutting, which forces the face to cave. The jets are then directed against the caved rock, which generally transforms it into uniformally sized sand. Water supplied through a 2-inch wash hose flows away from the face, carrying the sand to a small sand-laden water sump maintained in the floor of the tunnel about 10 feet back from the face. At this point the sand-laden water is picked up by the sand pump and transported out of the tunnel.

Procedure in advancing the face involves outlining the maximum size of the tunnel by directing the jets along the walls, back, and floor. The jet cut, which is usually 2 to 6 inches wide, is 3 to 4 feet deep. After the tunnel limits are outlined, the face is cut into a roughly rectangular pattern with 3 to 5 horizontal jet cuts and one vertical jet cut down the center. The bottom rectangular cuts are removed by directing the jets against those portions. The jets are then directed against the underside of the remaining hanging blocks, forcing them to cave from the face. Usually, an undercut is kept ahead of the face at all times. In exceptionally soft, uncemented zones, half the face may cave after the initial undercut has been made. Six-foot long pipes, which are attached to 1/2-inch whip hoses, allow the miners sufficient clearance from the caving rock at the face. Figures 1 and 2 show the initial jet cuts and the resulting caving of the rectangular blocks that have been undercut.

As the stream of water under pressure from the nozzle is moved slowly across the face of the tunnel, an open cut appears behind it. The broken rock, which has resulted from undercutting or from blasting, disintegrates under the impact of the jet. The resulting tunnel walls are smooth and even, without jagged edges.

Enough water is furnished by the jets and the 2-inch wash hose to carry the sand away from the face. A 3/4-inch mesh screen employed on the suction end of the sand pump, which is situated in a small sand-laden water sump about 10 feet back from the face, is observed carefully for hole enlargement or damage. Foreign material such as nails, bolts, and wood slivers will damage the rubber parts in the sand pumps, and extreme care is used when lining the upper half of the tunnel with timber or steel to insure that this type of material is not dropped on the floor of the tunnel.

In the process of cutting the face with jets, it is not uncommon to encounter large pieces of cemented sandstone (3 to 10 inches in diameter) locally known as "niggerheads." These "niggerheads" will not break by impact of the jet; however, they are easily disposed of by directing the jets onto the floor of the tunnel ahead of the sand-laden water sump and cutting out a hole large enough for several of the large cemented pieces. The "niggerheads" are thrown in the hole, and, when cutting is resumed in the face, water carrying sand flowing away from the face soon fills all voids in the hole and rebuilds the tunnel floor to its proper grade.

Actual mining of the sandstone is fairly simple, as the face can be advanced 4 to 6 feet in less than an hour. Other duties of the heading crew include lining the upper half of the tunnel with either timber or steel and maintaining the pumps. These operations, especially supporting the tunnel, involve considerable time. It is estimated by the resident engineer that the heading crews work towards advancing the tunnel only during half of the shift.

A 3-inch compressed-air line extends from a small 2-stage portable compressor at the surface to the heading of the tunnel. This line furnishes compressed air to a light jackhammer, which is used where the sandstone cannot be cut with water jets and drilling and blasting are necessary. A pneumatic pick using moil point steel is used for trimming the tunnel to proper size to install either timber or steel for tunnel support. The sandstone broken by blasting or by the pneumatic pick in trimming is reduced to small particles by the jets, washed away from the face, and pumped out of the tunnel by sand pumps.

After the tunnel has been excavated, a perforated drainage pipe is laid in the floor and enclosed and covered with 1-inch rock. The pipe is laid below grade and excavation is made with a pneumatic spade. The primary purpose of this pipe is to drain off the ground water to enable the concrete invert to be poured. The size of the drain depends on the amount of ground water found in the tunnel. In this case a 12-inch pipe was used. Mine rail is laid in the tunnel, and all supplies are hand-trammed to the tunnel face. A day-shift utility crew of four men trams all supplies to the heading and lays mine rails and water- and sand-discharge pipe.

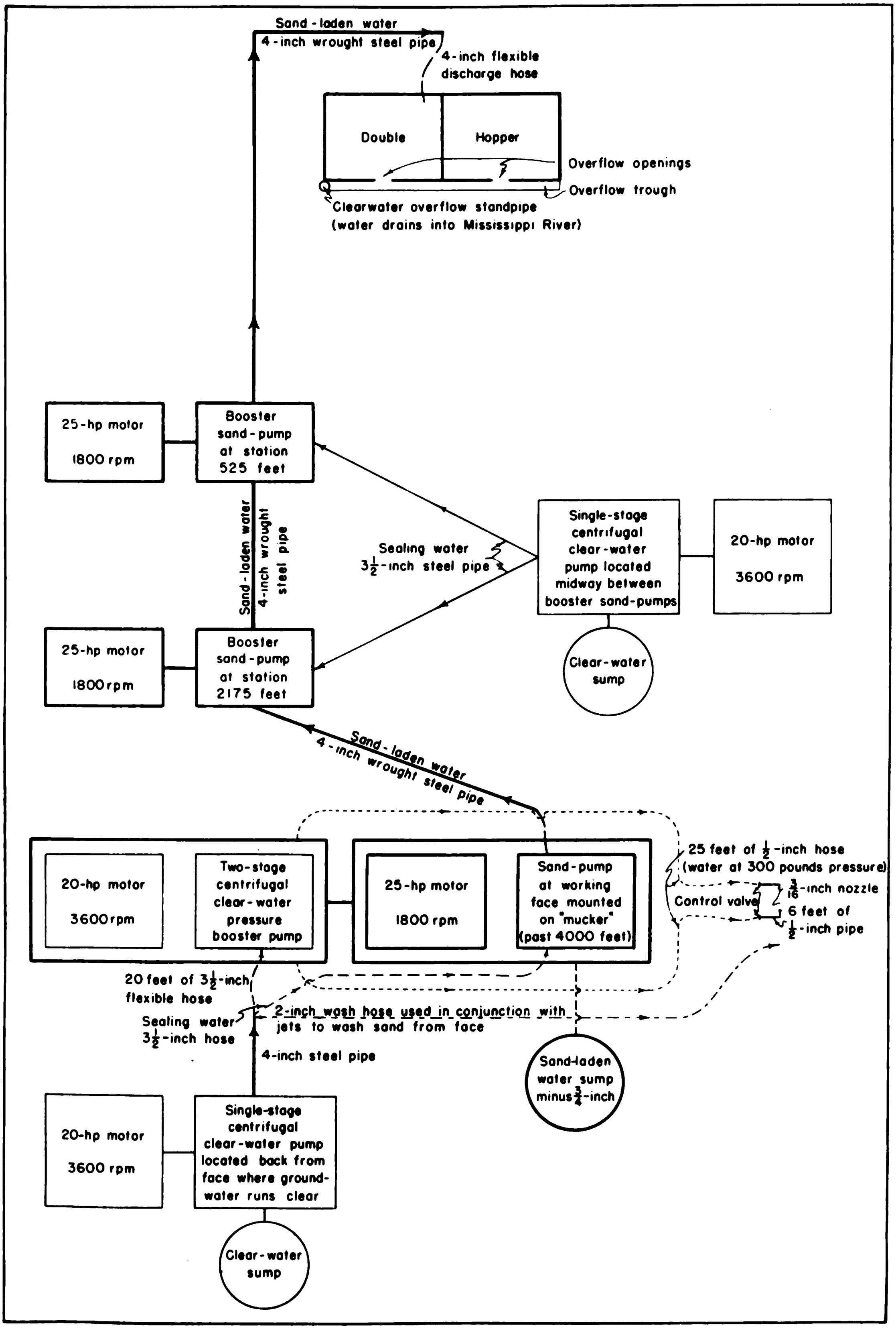

Sand-laden water
4-inch wrought steel pipe
4-inch flexible discharge hose
Double
Hopper
Overflow openings
Overflow trough
Clearwater overflow standpipe (water drains into Mississippi River)
25-hp motor 1800 rpm
Booster sand-pump at station 525 feet
Sand-laden water 4-inch wrought steel pipe
Sealing water 3$\frac{1}{2}$-inch steel pipe
Single-stage centrifugal clear-water pump located midway between booster sand-pumps
20-hp motor 3600 rpm
Clear-water sump
25-hp motor 1800 rpm
Booster sand-pump at station 2175 feet
Sand-laden water 4-inch wrought steel pipe
20-hp motor 3600 rpm
Two-stage centrifugal clear-water pressure booster pump
25-hp motor 1800 rpm
Sand-pump at working face mounted on "mucker" (past 4000 feet)
25 feet of $\frac{1}{2}$-inch hose (water at 300 pounds pressure)
Control valve
$\frac{3}{16}$-inch nozzle
6 feet of $\frac{1}{2}$-inch pipe
20 feet of 3$\frac{1}{2}$-inch flexible hose
Sealing water 3$\frac{1}{2}$-inch hose
2-inch wash hose used in conjunction with jets to wash sand from face
4-inch steel pipe
Sand-laden water sump minus $\frac{3}{4}$-inch
20-hp motor 3600 rpm
Single-stage centrifugal clear-water pump located back from face where ground-water runs clear
Clear-water sump

Figure 3. - Pump arrangement employed when tunneling has progressed past 4000 feet.

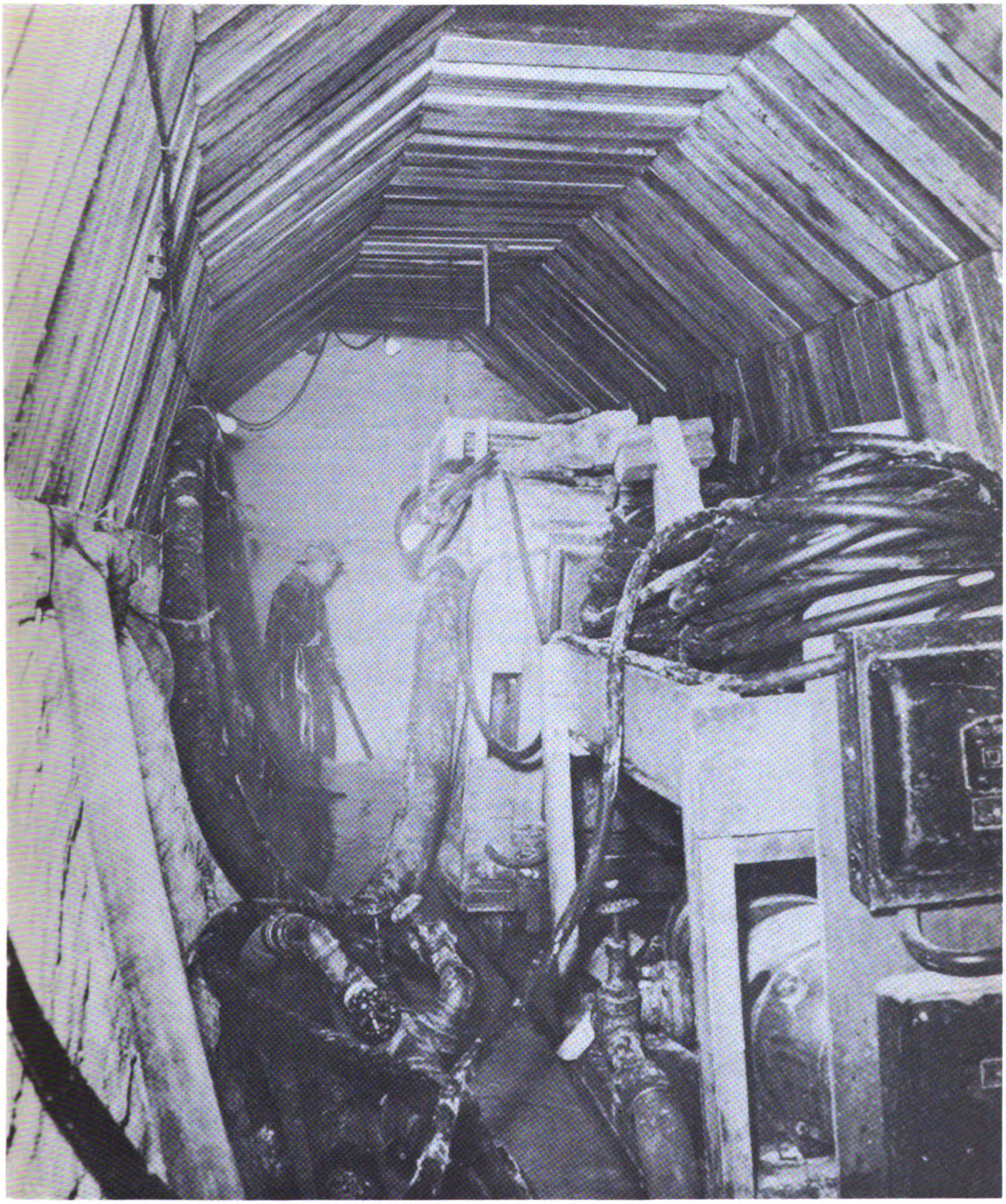


Figure 4. - The mobile "mucker" and "cutter" operation. (Courtesy, C. J. Kenison, Industrial Photography, Minneapolis, Minn.)

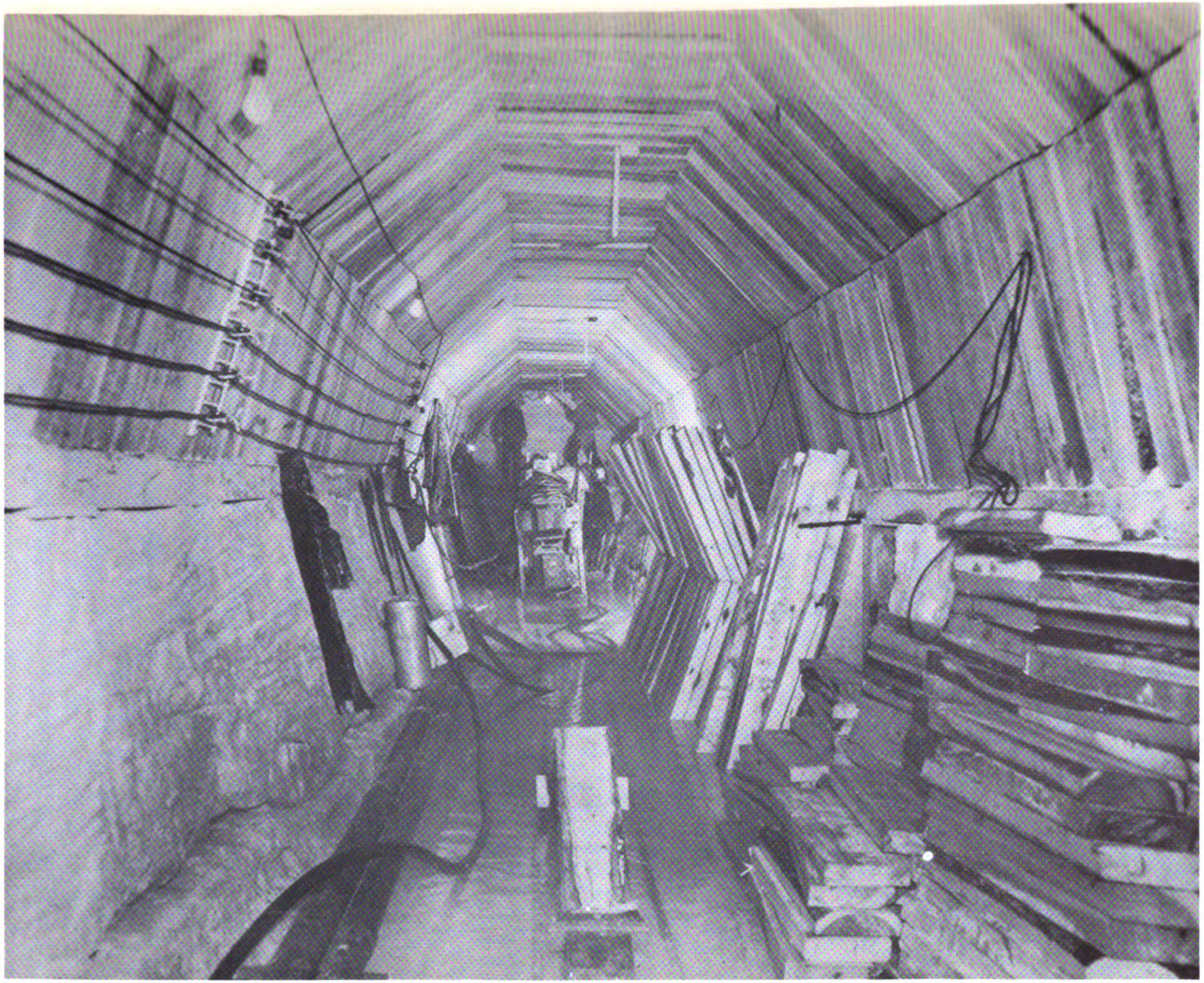


Figure 5. - Mobile "mucker" and "cutter" in the heading of the tunnel. (Courtesy, C. J. Kenison, Industrial Photography, Minneapolis, Minn.)

REMOVAL OF SAND

Rubber-lined sand pumps are used to transport the sand to a hopper near the portal of the tunnel. The pumps are designed to work against a head of 100 feet. Figure 3 is a sketch of the pump arrangement employed when hydraulic tunneling has progressed past 4,000 feet. With the design of pump in use, the maximum distance the sand can be pumped before boosting is approximately 2,000 feet.

A controlled flow of clear water (sealing water) at a pressure higher than the pump discharge is introduced into the rubber-lined sand pumps by single-stage centrifugal pumps. The clear water, which enters the sand pumps at a higher pressure than that of the sand-pump discharge, serves with the rubber lining to keep abrasive-laden water from coming into contact with metal parts of the pump. The discharge pressure on the sand pumps is maintained at 80 to 90 pounds (per square inch), and that of the sealing water is 100 to 110 pounds (per square inch). Seal pressure should be about 12 pounds (per square inch) higher than the discharge pressure.

As is shown in figure 3, the clear-water cutter pump and the sand pump at the working face of the tunnel are mounted on two movable rail trucks, which are hooked together and identified locally as a "cutter" and "mucker", respectively. The clear-water cutter pump behind the mucker is a 2-stage centrifugal powered by a 20-horsepower, 3,600-r.p.m., electric motor and furnishes water at 300 pounds pressure (per square inch) for the jets. The clear water for the cutter pump comes from another single-stage centrifugal pump, which also supplies sealing water for the "mucker" as well as water to the 2-inch hose for washing the sand from the face. This single-stage pump, which supplies clear water to the pump on the "mucker", is powered by a 20-horsepower, 3,600-r.p.m. motor and is situated back from the face. The tunnel can be advanced as far as 2,000 feet ahead before it has to be moved up. The jet nozzles, which are designed to fit a 1/2-inch pipe, have a 3/16-inch diameter orifice and are obtained from a local plumbing supply firm in Minneapolis. They are of the standard sprinkler type.

The sand pump or "mucker" is powered by a 25-horsepower, 1,800-r.p.m. motor. The pump draws the water carrying minus 3/4-inch material through a 3/4-inch mesh screen from a small sump maintained approximately 10 feet back from the face of the tunnel. A flexible discharge hose is used for connecting the pump to the main discharge line, which is a 4-inch wrought steel pipe. The discharge hose is two 20-foot lengths of 4-inch suction hose. This length permits the "mucker" to be advanced 40 feet ahead of the end of the main steel discharge pipe before additional pipe is required. Figures 4 and 5 show the "cutter" and "mucker" in the heading of the tunnel.

At the time of this writing, the sand-laden water was discharged through 1,825 feet of 4-inch steel pipe to an intermediate booster sand pump. The intermediate booster pump discharged through 1,650 feet of 4-inch pipe into another booster sand pump, which, in turn, discharged through a 4-inch pipe into a hopper at the surface. The "mucker" was approximately 4,000 feet from the portal, and the intermediate booster pump was 2,175 feet from the portal. The last booster pump, which discharges into the hopper, was 525 feet from the portal. The discharge pipe from this pump passes up through a drill hole, which has intersected the back of the tunnel from the surface and discharges the sand-laden water into the hopper. The hopper is situated almost vertically above the last booster pump.

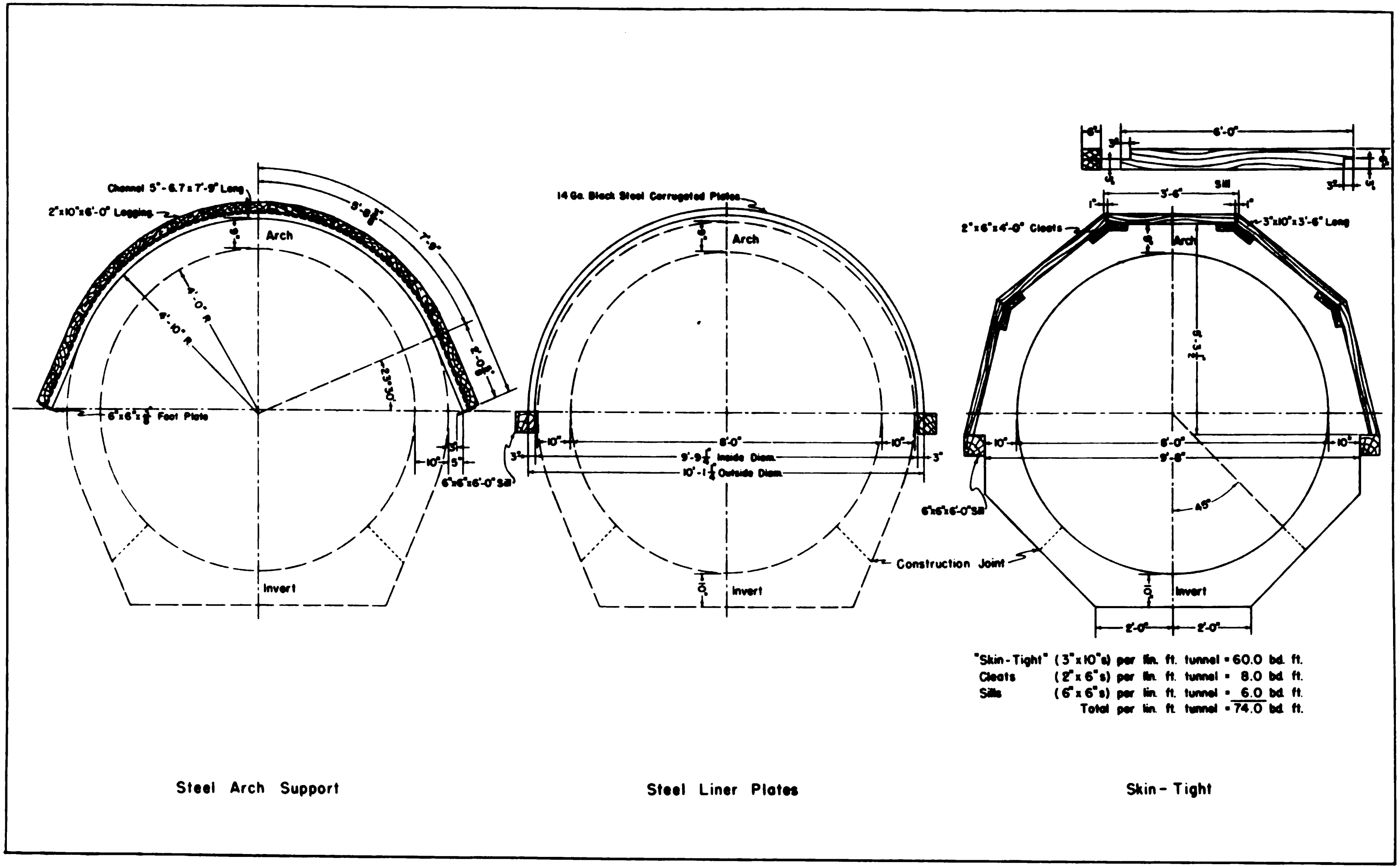
Each of the intermediate booster pumps at stations 2175 and 525 is powered by a 25-horsepower motor. Sealing water to each is from a nearby clear-water pump and is furnished through a 3-1/2-inch pipe by a single-stage, centrifugal, clear-water pump powered by a 20-horsepower motor.

The sumps for collecting the ground water to supply the clear-water pumps are situated at predetermined intervals of about 2,000 feet, the number of clear-water pumps and sumps in a tunnel depending on the length of the tunnel to be driven. The sumps are made by damming the tunnel to a height of about 18 inches above floor level. The water backs up in the tunnel for 1,000 feet, but this has no appreciable effect upon the speed of advance of the tunnel. Rails are laid over the dam on approaches from either side and are then under 18 inches of water. Considerable difficulty is experienced in hand-tramming supplies through the water to the face, but this difficulty is more than offset by the small cost of constructing the sump.

Ground-water flow has increased with the length of the tunnel. At station 4000, the ground flow supplies enough water to operate the jets, clear-water pumps, and sand pumps. The estimated flow at this writing is 2,000 gallons per minute. Overflow from the sumps passes through the tunnel, then into a by-pass near the portal of the tunnel, and finally into the Mississippi River.

The sand pumps, which constantly handle the abrasive material, have a low maintenance cost, and new rubber parts can easily be installed in the field. Most of 4-inch sand-discharge pipe has been used in other tunnel jobs. Its life cannot be estimated, but it is known that some of the pipe has been in use intermittently for 15 years. The life of rubber parts in the sand pumps varies considerably, depending on the size of the abrasive material, pressure of the sealing water, and the amount of foreign material, such as wood slivers, nails, and bolts, that passes through the screen. Under ideal conditions, with the pressure of the sealing water always 12 pounds or more above the discharge pressure of the sand pumps and with no wood slivers or bolts entering the pumps, the liners will last as long as 3 months. However, they have been destroyed in less than a day through oversize particles passing through an enlarged hole in the screen or through wood slivers or bolts puncturing the rubber.

The sand is removed from the surface hopper to a 5-cubic yard dump truck operating three shifts per 24-hour day. Disposal of the sand is somewhat of a problem within the city, and the final disjposal cost is a large factor in the over-all costs of the tunnel job. The hopper is



"Skin-Tight" (3"x10"s) per lin. ft. tunnel = 60.0 bd. ft.
Cleats (2"x6"s) per lin. ft. tunnel = 8.0 bd. ft.
Sills (6"x6"s) per lin. ft. tunnel = 6.0 bd. ft.
Total per lin. ft. tunnel = 74.0 bd. ft.

Figure 6. - Types of tunnel support for main storm sewer, Minneapolis, Minn.

situated on the bank of the Mississippi River. It has two bins, and the discharge material can be directed into either. The sand quickly settles out of the water, and the bin is filled to an overflow opening near the top. The material from the sand pump is discharged into a bin as long as the overflow water runs clear. When the overflow water starts carrying sand through the opening, the discharge is transferred to the other bin. The clear overflow water is troughed to a standpipe, thence down the drill hole, which serves as a passageway for the sand discharge pipe, and into the tunnel by-pass, which carries the excess ground water to the Mississippi River.

The hopper empties from the bottom. The sand grains are well-rounded, and no trouble is experienced from sand packing. Water that leaks through the hopper to the loading gate flows into a trough and is carried to the standpipe that drains the trough leading from the overflow openings in the bins.

The sand is used throughout the City of Minneapolis for fill, ballast, and a variety of other purposes.

TUNNEL SUPPORT

Three methods of temporarily supporting the tunnel are used in the main storm sewer. They are (1) steel-arch support, (2) steel liner plates, and (3) skin-tight. The method of support is determined by the type of ground. Steel-arch support is used in areas where the rock is more or less indurated and the walls and back will stand without sloughing. Steel liner plates and skin-tight are used in areas where the rock is soft and friable and the walls and back tend to slough.

Figure 6 shows the types of tunnel support used and the general cross section of the tunnel.

Steel-Arch Support

Steel-arch supports are 5-inch channels 15 feet 6 inches long and weighing 6.7 pounds per foot. The steel channels are preformed into partly semi-circular members with a 4-foot 10-inch radius and flared out 5 inches just above the horizontal center line (fig. 6). Six by 6 by 3/8-inch foot plates are welded to the ends. Notches are cut in the walls for the foot plates to rest upon, and supporting posts are not required. Weight from the back forces the foot plates to push solidly against the sandstone walls. This type of support is used only where the ground is more or less cemented.

The channels are spaced 6 feet, center to center. Two by 10-inch lagging is laid lengthwise between them; thus, the upper half of the tunnel is solidly lined. Estimated cost of material for this type of tunnel support is $3.95 per linear foot.

Steel Liner Plates

Steel liner plates are arc segments of 14-gage, black-steel, corrugated plates 24 by 48 inches in area. These arc segments are bolted together to form a half circle. The half-circle members are set in place, and the adjoining half-circle members are bolted by flanges to each other in turn, thus solidly lining the upper half of the tunnel.

The liner plates rest on 6 by 6-inch by 6-foot sills situated at the horizontal center line of the tunnel and set in grooves cut in the wall with a light pneumatic pick. Posts are used to support the sills only where the sandstone is soft and friable; post grooves also are cut with a pneumatic pick.

Recent practice with this type of support has been to omit one arc segment plate from every other half-circle member, leaving this member 48 inches short of a half-circle. The vacant area is divided equally between both sides of the tunnel, and neither end of member rests upon the sill; however, the side of the member is bolted to the adjoining side of the preceding and succeeding member. Although this method leaves a 24 by 24-inch open space on each wall of the tunnel, no rock falls or sloughing have been noted from the unlined areas.

Figure 7 shows the liner-plate type of tunnel support at a point where a change-over has been made from liner plates to timber. The alternate open spaces in the liner-plate section can be seen on the left wall.

Estimated cost of material for the liner-plate type of support is $7.53 per linear foot of advance. Although the cost of material is high, installation costs are low. Speed in lining the tunnel and the resulting saving in man-hours of labor serve to make this method almost as cheap to use as the other methods of tunnel support.

Skin-Tight

Skin-tight tunnel support is that method wherein the upper half of the tunnel is lined solidly with timber. A set consists of five pieces of timber each 3 by 8 inches by 3 feet 6 inches long, joined together end to end to form a half-decagon member. The ends rest on 6 by 6-inch sills 6 feet long. The sills are set in the manner described in the steel liner-plate method, and post supports for the sill are used where the sandstone is soft and friable.

The half decagon members usually are partly assembled before setting in place in the tunnel. Figure 5 shows portions of the assembled pieces along the right wall of the tunnel. The members are laid in succession, and each succeeding member butts tightly against the previous one; thus, the upper half of the tunnel is solidly lined. The skin-tight method of tunnel support is shown in figure 7 at a point where a change-over has been made from liner plates to timber.

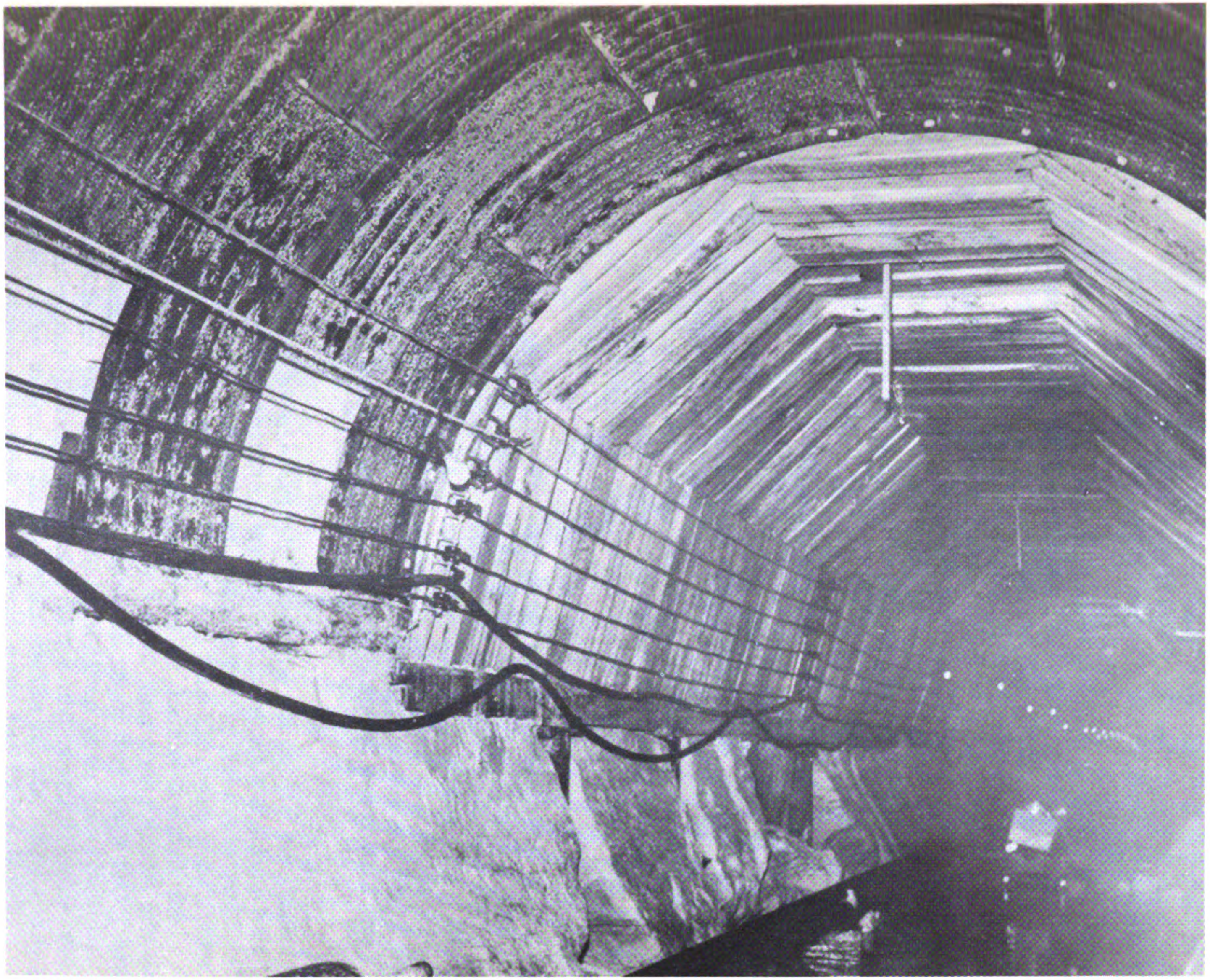


Figure 7. - Changing over from steel liner plates to skin-tight method of tunnel support.
(Courtesy, C. J. Kenison, Industrial Photography, Minneapolis, Minn.)

Estimated cost of the material for this method is $4.10 per linear foot of advance.

All tunnel support lining will be left in place when the tunnel is concreted to finished circular shape. Concrete will be mixed on the surface and pumped down drill holes that intersect the tunnel at intervals.

Standard steel forms will be used in concreting, and 90 to 100 feet of tunnel will be concreted at each setting. The invert will be poured first and will be provided with proper construction joint. Arch pours will follow when required arch forms are set on the finished inverts and the cement time has elapsed.

Drainage is provided by the buried 12-inch perforated pipe, or, if this will not carry the full flow, the tunnel is dammed and the water is pumped over the cementing area.

VENTILATION

Fans are used when ventilation is necessary. Fresh air is obtained through the steel-cased, 8-inch-diameter drill holes put down from surface along the projected center line of the tunnel. These drill holes are approximately 1,600 feet apart and are used primarily for pumping concrete into the tunnel. The concrete pump can transport concrete a maximum distance of 800 feet each way from the drill hole; therefore, the holes cannot be farther apart than 1,600 feet.

The drill holes are used also for bringing power lines into the tunnel, thus permitting transformers to be kept close to the face and eliminating elaborate cable systems. The present power-line system permits transmission of the power for an approximate distance of 3,000 feet. Normal practice is to install transformers at the collar of the drill hole and drop power lines down the hole in a 4-inch fire hose. The fire hose serves as insulation and protection against ground water that may seep into the drill hole.

The tunnel is lighted by electricity from the portal to the face. The pumps are powered by electricity, and the electric-power lines are hung on the lined section of the wall and supported by brackets and insulators. There are three 440-volt lines and one 110-volt line. The cable used for transmitting power to the pumps is double-braided and rubber-covered. All controls are fully enclosed, and connections are made with solderless connectors covered with cambric tape, friction tape, and rubber tape. Inasmuch as the tunnel is being driven with the floor at approximately ground-water level, the power lines and control boxes are not seriously affected by water. The back and walls of the tunnel are comparatively dry, and water enters the tunnel near the floor level.

DRAINAGE

The tunnel is drained by a 12-inch perforated pipe surrounded and covered with 1-inch rock, buried below grade on the north side of the tunnel. This pipe carries the ground water to a tunnel by-pass near the portal, which in turn drains the water into the Mississippi River. However, if the ground-water flow is too large to be carried by the drainage pipe, the water flows over the floor of the tunnel, into the tunnel by-pass, and on into the Mississippi River.

The size of the perforated drainage pipe is determined by the ground-water flow estimated to be encountered in the completed tunnel length. At times the tunnel-water flow will exceed the capacity of the pipe, but usually, over a long period of time, the tunnel will gradually drain until the pipe can carry all water that seeps into the tunnel. The primary purpose of the drain is to keep the tunnel floor free of water when concreting the inverts in the tunnel. If the tunnel flow exceeds the pipe capacity during concreting, the procedure is to dam the tunnel ahead of the concreting operation and pump excess water over the invert forms.

HYDRAULIC TUNNELING COST

The tunnel operation is conducted on a 3-shift, 5-day week basis. A 4-man crew consisting of 1 miner and 3 tunnel laborers works in the tunnel heading. Their work includes excavating and tunnel support. On the day shift, an additional 4-man utility crew advances the pipe and rail and trucks in timber and supplies needed for all shifts. The total labor required for a 24-hour period follows:

Workmen	No.	Rate/hr.	
Miners	3	$2.13	Tunnel heading (mining and timbering).
Tunnel laborers	9	1.70	Tunnel heading (mining and timbering)
Utility crew	4	1.70	Trucking supplies and advancing pipe and rail.
Electricians	1	2.20	
Laborers on sand hopper	3	1.70	Watching discharge and loading truck
Bookkeeper	1	1.70	
Truck drivers	3		Removing sand from hopper.

With the exception of the truck drivers, 21 men are employed on the tunnel job during a 24-hour day.

An average labor-cost breakdown on the main tunnel in payroll periods between January 1, 1949, and June 28, 1949, is shown in table 2. The table does not include supervision, cost of rail and pipe, or the amortization cost of pumps and compressed-air equipment. The payroll total column includes the total labor cost, with the exception of the truck drivers. Approximately one-half of the total labor cost per foot of advance can be charged to timbering and one-half to advancing the tunnel face.

TABLE 2 - Cost breakdown between January 1, 1949, and June 28, 1949 (main storm sewer)

Period	Number of days worked	Number of shifts	Total advance, feet	Average advance per day feet	Average advance per shift feet	Payroll total	Total labor cost per foot	Sand-disposal truck and driver	Cost per foot of advance truck and drivers	Material cost 1/	Material cost per foot of advance
Jan. 1-Jan. 14	9-2/3	29	351	36.3	12.1	$3,021.76	$8.61	$825.40	$2.35	$1,999.89	$5.70
Jan. 15-Jan. 28	10	30	358	35.8	11.9	3,217.49	8.99	860.53	2.40	1,374.72	3.84
Jan. 29-Feb. 11	10-1/3	31	325	31.5	10.5	3,273.59	10.07	901.26	2.77	1,248.00	3.84
Feb. 12-Feb. 25	8-2/3	26	281	32.4	10.8	2,958.94	10.53	716.90	2.55	1,079.04	3.84
Feb. 26-Mar. 11	10	30	330	33.0	11.0	3,520.62	10.67	873.80	2.65	1,353.00	4.10
Mar. 12-Mar. 25	10	30	266	26.6	8.9	3,319.65	12.48	831.01	3.12	1,055.05	3.97
Mar. 26-Apr. 8	10	30	208	20.8	6.9	3,369.90	16.20	812.00	3.90	843.80	4.06
Apr. 9-Apr. 22	9	27	337	37.4	12.5	2,968.23	8.81	796.00	2.36	1,340.30	3.98
Apr. 23-May 6	10	30	353	35.3	11.8	3,341.60	9.47	840.00	2.38	1,447.30	4.10
May 7-May 20	10	30	342	34.2	11.4	3,299.91	9.65	840.00	2.46	1,381.20	4.04
May 21-June 3	9	27	268	29.7	9.9	2,999.93	11.19	756.00	2.82	1,089.05	4.06
June 4-June 17	10	30	271	27.1	9.0	3,207.98	11.84	840.00	3.10	1,111.10	4.10
June 18-June 28	6-1/3	19	168	26.5	8.8	2,147.78	12.78	504.00	3.00	688.80	4.10
			3,858			40,647.38	10.53	10,396.90	2.69	16,011.25	4.15

1/ Includes steel ribs, liner plates, timber, power lines and repairs. Does not include pipe or rail.

With the pump arrangement shown in figure 3, power costs average $435. per month, or approximately $0.68 per linear foot of advance. A summary of the labor, power and material cost between January 1, 1949, and June 18, 1949 is shown in table 3.

TABLE 3 - Summary of labor, power and material costs between January 1, 1949 and June 18, 1949 (main tunnel)

Account	Total Cost	Feet advanced	Cost per foot advanced	Cost per foot of advance accumulat
Payroll	$40,647.38	3,858	$10.53	$10.53
Material	16,011.25	3,858	4.15	14.68
Power	2,610.00	3,858	.68	15.36
Sand disposal	10,396.90	3,858	2.69	18.05